Energy-Based Performance Modeling for Photovoltaic Systems

D. L. King, W. E. Boyson, and J. A. Kratochvil
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Energy production should be the primary basis for designing photovoltaic systems, and for long-term monitoring of system performance. An accurate performance model based on established testing procedures is required during the design phase to confidently predict expected system performance, and in order to compare actual versus expected energy production over the lifetime of the system. This paper discusses performance metrics used for commercial photovoltaic modules and systems, uses a comprehensive performance model to compare energy available from different module types, summarizes the dominant factors influencing system energy production, and illustrates how energy-based performance modeling can improve the performance and reliability of systems.

1. Introduction

The importance of good system design, installation practices, and reliability cannot be overemphasized, because without these elements it is impossible for photovoltaic modules to provide the energy of which they are capable. Energy-based system performance modeling provides the tool necessary to optimize system design and to gauge the performance of systems after they are installed.

2. Module and System Performance Metrics

The performance of photovoltaic modules and arrays can be reported and compared in different ways; efficiency or peak power (W_p) at the ASTM Standard Reporting Condition (SRC) [1], cost per peak watt at the SRC ($\$/W_p$), dc-energy normalized by peak power (kWh/W_p) [2], or average dc-energy produced per day (kWh/d). System performance is typically judged based on ac-energy delivered (kWh-ac/d) [3, 4], and perhaps the most definitive performance metric quantifies energy cost ($/kWh-ac) where installation cost, operation and maintenance costs, and long-term component degradation rates are considered.

The most commonly used performance metrics are probably efficiency and module $\$/W_p$. Table 1 summarizes the range for efficiency for different commercially available PV module technologies, including cell efficiency inside the modules. These efficiencies were calculated from manufacturer's power specifications at SRC and total module area. The module cost-per-peak-watt metric, $\$/W_p$, continues to be widely used by the module industry. Unfortunately, neither of these metrics address module energy production, array size, thermal behavior, system component matching, reliability, or O&M costs. Therefore, the efforts summarized in this paper have been aimed at improving testing and modeling procedures used to predict the expected energy produced by photovoltaic systems designed for site-dependent applications.

Table 1: Efficiency ranges for commercial modules and cells at ASTM Standard Reporting Condition.

Technology	Cell Eff. (%)	Module Eff. (%)
mc-Si	11 - 14.5	9 - 13
c-Si	12 - 16	10 - 13.5
a-Si	5 - 7.5	5 - 6.5
CIS	10 - 11.5	7.5 - 9.5
CdTe	7.5 - 10	7 - 9

3. Performance Modeling Procedure

The comprehensive outdoor testing procedures and array performance model developed by Sandia have now demonstrated good accuracy over a wide range of operating conditions, as documented elsewhere [5, 6, 7, 8, 9]. The performance model accounts for module specific electrical parameters, temperature coefficients, operating temperature as a function of environmental conditions, optical losses at high angles of incidence, solar spectral variation over the day, and module mounting orientation or tracking options. A sensitivity analysis of the factors influencing the energy available from modules was recently documented [10].

Our performance model was coupled with solar resource and meteorological data from the National Solar Radiation Database (NSRDB) [11] to calculate the expected annual energy production for a variety of module technologies. Table 2 gives the results for modules oriented at latitude-tilt, in terms of their expected average energy production per day. Results were scaled to the equivalent of a 1-kW_p array for each technology. Normalized values, with respect to the "mc-Si" module, are also shown for more direct comparison. To illustrate site dependence, three locations were selected for analysis: Albuquerque, Sacramento, and Buffalo. An important result from this analysis was that given an equivalent power rating at SRC all PV technology types were nominally equivalent in terms of expected annual energy production, within the uncertainty of the calculation (~±5%). This conclusion was also recently supported in results reported by others [12].

4. Factors Influencing System Energy Production

Developing a fundamental understanding of the factors influencing the expected dc-energy production for individual photovoltaic modules is a significant step toward quantifying the levelized energy costs for PV power systems. However, the module-level factors previously discussed must be put in perspective relative to system-level factors that can overwhelm them. Losses associated with these system-level factors result in less energy delivered to the load than the array is capable of providing, thus a low

Table 2: Calculated annual-average daily dc-energy (kWh/d) available from different PV technology types all with identical 1 kW_p ratings.

Latitude-Tilt Orientation (Uncertainty in values +/- 5%)									
	mc-Si	mc-Si#2	c-Si	p-Si	a-Si	a-Si#2	CIS	CdTe	CdTe#2
Albuquerque	5.82	5.87	5.88	5.67	6.46	5.80	6.07	5.73	6.56
Sacramento	4.90	4.95	4.95	4.72	5.43	4.83	5.03	4.83	5.65
Buffalo	3.87	3.89	3.97	3.74	4.24	3.80	3.92	3.87	4.25
Normalized	mc-Si	mc-Si#2	c-Si	p-Si	a-Si	a-Si#2	CIS	CdTe	CdTe#2
Albuquerque	1.00	1.01	1.01	0.97	1.11	1.00	1.04	0.99	1.13
Sacramento	1.00	1.01	1.01	0.96	1.11	0.99	1.03	0.99	1.15
Buffalo	1.00	1.00	1.02	0.96	1.09	0.98	1.01	1.00	1.10

“array utilization.” The magnitude of the associated energy losses is dependent on system design, module and BOS component selection, and weather conditions at the site. Nonetheless, Table 3 is an attempt to rank the module and system factors influencing energy production, along with an estimated range for their impact. In poorly designed or installed systems, combinations of these factors can quickly result in the inability of the system to power the intended load, constituting a “system failure.”

Table 3: Module and system-level factors influencing the energy available from PV system, estimated ranges.

Factor	*Range (%)*
Module orientation	-25 to +30
Energy storage (batteries)	-30 to -5
Array utilization losses	-30 to -5
Power conditioning hardware	-20 to -5
Module power specification	-15 to 0
Module temperature coefficients	-10 to -2
Module (array) degradation (%/yr)	-7 to -0.5
Module V_{mp} vs. Irradiance	-5 to +5
Module soiling (annual average)	-10 to 0
Angle-of-incidence optical losses	-5 to 0
Module mismatch in array	-5 to 0
Solar spectral variation	-3 to +1

5. Array Utilization Example

Array utilization losses are common in battery charging systems because charge controllers rarely have a maximum-power-point tracking capability. They are also present in grid-tied systems if the array maximum-power voltage (V_{mp}) is outside acceptable limits for the inverter or if the array maximum-power (P_{mp}) exceeds the inverter capacity. In both cases, inadvertent array shading and solar tracking error can also result in array utilization losses.

An example of how modeling can be used to understand and improve the performance of systems, and as a result avoid system reliability problems in the field, is illustrated in Figure 1. This stand-alone system was designed for small remote residential applications requiring about 2 kWh-ac/d of electrical energy. A high-performance array was added to the system to ensure that the load was met. Unfortunately, for an Albuquerque site, the array performance characteristics were not a good match with the “voltage window” dictated by the requirements for correctly charging the batteries. Only about 20% of the annual energy available from the array occurred with an array V_{mp} within the voltage window. The rest of the time the operating voltage was well below the array V_{mp}, resulting in “array utilization” over the year of about 85%, directly reducing the ac-energy available. Moving the system to Phoenix would help in that the V_{mp} distribution for the year shifts about 2V lower, more within the operating window. However, moving the system to Alamosa, CO, would make things worse in two ways. The V_{mp} distribution would shift higher by about 1.5V, thus worse than Albuquerque for array utilization. In addition, colder ambient temperatures would result in lower battery temperatures. To compensate for the low temperature, the charge controller may raise the bulk charging voltage over 31Vdc, which exceeds the input voltage range for the inverter, which in turn will shut down the inverter intermittently. To the owner in Alamosa, the system would then have “failed,” and probably the inverter would be blamed rather than the array selection during system design.

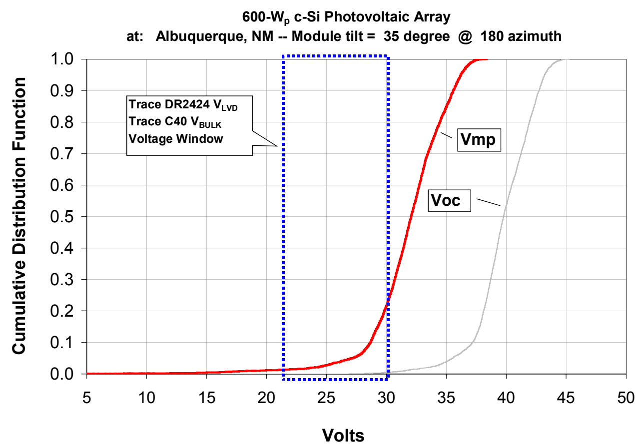

Figure 1: Cumulative distribution of hourly energy available from array over the year versus V_{mp} and V_{oc} relative to “operating window” defined by the batteries.

6. References

[1] Standard Test Procedure, ASTM E 1036.
[2] S. Ransom, et al., 20th IEEE PVSC, 2000, 1505-1508.
[3] T. Townsend, et al., *1st WCPEC*, 1994, 1036-1039.
[4] M. C. Russell, *1st World WCPEC*, 1994, 1040-1043.
[5] D. King, et al., *2nd World PVSEC*, 1998, 1947-1952.
[6 D. King, et al., *26th IEEE PVSC*, 1997, 1113-1116.
[7] B. Kroposki, et al., *28th IEEE PVSC*, 2000, 1407-1411.
[8] C. Whitaker, et al., *26th IEEE PVSC*, 1997, 1253-1256.
[9] Maui Solar Energy Software Corporation, http://www.mauisolarsoftware.com
[10] Sandia’s PV Program Quarterly Highlights, http://www.sandia.gov/pv/hot/quarterly.htm
[11] Anon., “NSRDB Vol.2.”, NREL/TP-463-5784, 1995.
[12] S. Ransome and J. Wohlgemuth, “Analysis of Measured kWh/kWp from Grid-Tied PV Systems – Modeling Different Technologies Worldwide with Real Data,” submitted for 17th European PVSEC, Munich, 2001.